hep-ph/0502150
IPM/P-2005/008
UCLA/05/TEP/6

Pulsar Kicks from Majoron Emission

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(Dated: February 2, 2008)

We show that Majoron emission from a hot nascent neutron star can be anisotropic in the presence of a strong magnetic field. If Majorons carry a non-negligible fraction of the supernova energy, the resulting recoil velocity of a neutron star can explain the observed velocities of pulsars.

PACS numbers: 13.15.+g,14.60.St,97.60.Jd
Keywords: neutrino, Majoron, supernova, pulsar velocities

I. INTRODUCTION

Pulsar velocities present a long-standing puzzle [1]. The distribution of pulsar velocities is non-gaussian, with an average velocity (250–500) km/s [2, 3]. However, as many as 15% of pulsars have velocities greater than 1000 km/s [3]. Pulsars are magnetized rotating neutron stars born in supernova explosions of ordinary stars, and so one expects these high velocities to originate in the supernova explosions. However, a pure hydrodynamical asymmetry does not seem to be sufficient to account for such high velocities. According to advanced 3-dimensional calculations, pulsar velocities from an asymmetric collapse alone should be lower than 200 km/s [4]. Some earlier papers have claimed somewhat greater velocities, but, by any account, it seems unlikely that the asymmetries in the collapse could explain the high-velocity population with speeds in excess of 1000 km/s.

A much greater energy pool is in neutrinos that take away 99% of the supernova energy. Even an anisotropy as small as a few per cent in the neutrino emission is sufficient to explain the observed pulsar velocities. Of course, the neutrinos are produced in weak processes whose rates depend on the angle between the neutrino momentum and the electron spin. In the strong magnetic field of a pulsar the electrons are polarized, and neutrinos are produced with a considerable anisotropy. It was suggested that the weak interactions alone could lead to an anisotropic flux of neutrinos and explain the pulsar kicks [5]. However, the asymmetry is quickly erased by scattering of the neutrinos on their way out of the neutron star. In fact, one can show that, in an approximate thermal and chemical equilibrium an anisotropy in production or scattering amplitudes cannot result in an anisotropic flux [6].

There are two ways to evade this no-go theorem [6]. One is to consider an ordinary neutrino outside its neutrinosphere, where it is *not* in thermal equilibrium. For example, conversions from one neutrino type to another between their respective neutrinospheres, in the area where one of them is trapped, but the other one is free-streaming, could explain the pulsar kicks [7]. However, present constraints on the neutrino masses do not allow the resonant neutrino oscillations to take place at densities around the neutrinospheres, and so this mechanism does not work.

Another possibility is that there is a new particle, whose interaction with matter is even weaker than that of neutrinos such that it is produced out of equilibrium. Then the no-go theorem of Ref. [6] does not apply. It has been proposed that an asymmetric emission of sterile neutrinos could explain the pulsar kicks [8]. In this paper we consider a different mechanism, based on the emission of Majorons from a cooling newly-formed neutron star.

Majorons, Φ, are massless pseudo-scalar particles [9] which, to a good approximation, have interactions only with neutrinos described by the Lagrangian

$$\mathcal{L}_{\rm int} = \frac{\Phi}{2}(g_{\alpha\beta}\nu_\alpha^T\sigma_2\nu_\beta + g^*_{\alpha\beta}\nu_\beta^\dagger\sigma_2\nu_\alpha^*). \tag{1}$$

The role of the Majoron emission in the supernova cooling process has been studied extensively [10, 11]. Inside a supernova core neutrinos have an effective potential given by

$$\mathcal{L}_{\rm eff} = -\nu_\alpha^\dagger V_{\alpha\beta}\nu_\beta, \tag{2}$$

where $V_{\alpha\beta} = {\rm diag}(V_e, V_\mu, V_\tau)$ and

$$V_e = \sqrt{2}G_F n_B(Y_e + 2Y_{\nu_e} - Y_n/2), \tag{3}$$

$$V_\mu = V_\tau = \sqrt{2}G_F n_B(Y_{\nu_e} - Y_n/2). \tag{4}$$

Here, $Y_i = (n_i - \bar{n}_i)/n_B$ and n_B is the baryon density. We note that, for the values of the Majoron couplings we consider, the terms in the potential due to the Majoron exchange [12] are negligible; in other words, $|g_{\alpha\beta}|^2 n_B Y_\nu/T^2 \ll V_e, V_\mu$.

Because of the nonzero effective potential, the dispersion relations of neutrinos and antineutrinos inside the core are different, making processes such as $\nu\nu \to \Phi$ and $\bar{\nu} \to \nu\Phi$ kinematically possible. These processes give rise to a Majoron flux, which can transfer some energy, E_Φ, from the core. Obviously, E_Φ cannot be as high as the total supernova energy, $E_{\rm total} = (1.5 - 4.5) \times 10^{53}$ erg. This is because neutrinos form supernova 1987A have been observed, and this observation implies that at least a third of $E_{\rm total}$ was emitted in neutrinos. Based on this observation, one can derive strong bounds on the couplings [10, 11]:

$$g_{ee} < 4 \times 10^{-7} \quad g_{\mu\mu}, g_{\tau\tau} < 10^{-6} \quad . \tag{5}$$

However, the data from SN1987a are not precise enough to rule out the possibility that E_Φ was a non-negligible fraction of $E_{\rm total}$. Let us define

$$x \equiv E_\Phi / E_{\rm total}, \tag{6}$$

and let us assume that the emission of Majorons is anisotropic, with an asymmetry ϵ of a few percent. Then the overall anisotropy is ϵx. If this quantity is of the order of 10^{-2}, the anisotropic emission would give the neutron star a recoil consistent with the observed pulsar velocities. We will show that the neutron star's magnetic field can cause such an asymmetry.

Let us examine whether the Majorons are trapped. Inside a supernova core, the processes $\Phi \to \nu\nu$ and $\nu\Phi \to \bar{\nu}$ are kinematically allowed. Indeed, if the couplings are very large ($g > 10^{-5}$), the Majorons are trapped inside the core so they cannot transfer a significant amount of energy to the outside [10]. Thus, the bounds from supernova cooling exclude only a small window in the coupling constant values. In this paper, we will concentrate on the coupling constant values that saturate the bounds in eq. (5). For such small values of the couplings, the mean free path of $\bar{\nu}\Phi \to \nu$ is two orders of magnitude larger than the radius of the supernova core [11]. The Majoron decay length is even larger. As a result, one can assume that the Majorons leave the core without undergoing any interaction or decay. Also as it is discussed in [11], for the values of coupling satisfying the upper bounds (5), the four particle interactions involving Majorons, such as $\Phi\nu \to \Phi\nu$, $\nu\nu \to \Phi\Phi$ and etc., are negligible.

Now let us assume that there is a uniform strong magnetic field in the core along the $\hat{z}$-direction: $\vec{B} = |\vec{B}|\hat{z}$. In the presence of such a magnetic field the medium is polarized [13], and the average spin of electrons is

$$\langle \vec{\lambda}_e \rangle = -\frac{e\vec{B}}{2} \left(\frac{3}{\pi^4} \right)^{1/3} n_e^{-2/3}. \tag{7}$$

As a result, the effective potential of neutrinos receives a new contribution, δV [13]:

$$\delta V = -\sqrt{2} G_F Y_e n_B \langle \lambda_e \rangle \cos\theta {\rm diag}(3/2, 1/2, 1/2), \tag{8}$$

where θ is the angle between the neutrino momentum and the direction of polarization. Since the effective potential of the neutrinos depends on the direction of their momentum, the rates of the processes $\nu\nu \to \Phi$ and $\bar{\nu} \to \nu\Phi$ will also depend on the direction. The emission of Majorons produced in these three-particle processes is strongly correlated with the direction of the initial neutrinos [11]. Therefore, the Majoron emission will be anisotropic.

We stress that in all our discussion we neglect the neutrino magnetic moment, which is very small in the Standard Model with massive neutrinos. The magnetic field affects the neutrinos only indirectly, through polarizing the electrons in the medium. If some new physics makes the neutrino magnetic moment non-negligible, it may have implications for the pulsar kicks [14].

The rest of this paper is organized as follows. In sect. II, we will evaluate the momentum that the process $\nu_e\nu_e \to \Phi$ can exert on the neutron star in terms of the total energy transferred to Majorons. In sect. III, we will perform the same analysis for the processes $\nu_\mu\nu_\mu \to \Phi$ and $\bar{\nu}_\mu \to \Phi\nu_\mu$. In sect. IV, we summarize our conclusions and discuss the effects of a realistic configuration of the magnetic field, which is probably not a pure dipole.

II. EFFECTS OF $\nu_e\nu_e \to \Phi$

During the first few seconds after the core collapse, inside the inner core ($r < 10$ km), the electron neutrinos are degenerate: $\mu_{\nu_e} \sim 100 - 200$ MeV and $T \sim 10 - 40$ MeV [15]. Right after the core bounce V_e is positive, which makes the process $\nu_e \to \bar{\nu}_e\Phi$ kinematically allowed. However, after about one second V_e becomes negative and instead of ν_e-decay, $\nu_e\nu_e \to \Phi$ becomes the source for the production of Φ. As discussed in Ref. [11], the time during which V_e is positive is too short to be important for energy depletion (or momentum transfer). Thus, we concentrate on the time when $V_e < 0$.

Consider two electron neutrinos with momenta

$$p_1 = |\vec{p}_1|(1, \sin\theta_1, 0, \cos\theta_1)$$

and

$$p_2 = |\vec{p}_2|(1, \sin\theta_2\cos\phi, \sin\theta_2\sin\phi, \cos\theta_2).$$

The cross-section of $\nu_e(p_1)\nu_e(p_2) \to \Phi$ is given by [11]

$$\sigma = \frac{2\pi g_{ee}^2}{4p_1^2p_2^2|v_1 - v_2|}(p_1+p_2)|2V_e+\delta V_1+\delta V_2|\delta(\cos\theta_3-\cos\theta_0) \tag{9}$$

where $\cos\theta_3 = \vec{p}_1 \cdot \vec{p}_2/(|\vec{p}_1||\vec{p}_2|)$ and

$$\cos\theta_0 = 1 + (p_1 + p_2)(2V_e + \delta V_1 + \delta V_2)/(p_1p_2). \tag{10}$$

Note that δV_1 and δV_2 depend on the directions of $\vec{p}_1$ and $\vec{p}_2$. Integrating over all possible momenta of the neutrinos, we find that the neutrinos inside a volume dV

during time $d\tau$, transfer a momentum to the core which can be estimated as

$$d\vec{P} = \frac{7\sqrt{2}}{24} G_F n_e \langle \vec{\lambda}_e \rangle \frac{|g_{ee}|^2}{(2\pi)^3} (\mu_{\nu_e})^4 dV d\tau. \quad (11)$$

Of course, the process $\nu_e\nu_e \to \Phi$ speeds up the deleptonization process and, therefore, the duration of the neutrino emission becomes shorter. However, for $g_{ee} < 4 \times 10^{-7}$, $\Gamma(\nu_e\nu_e \to \Phi) \ll \Gamma(ep \to \nu_e n)$ and we expect that the β-equilibrium is maintained, and the overall evolution of the density profiles is similar to the case without Majoron emission [15].

Since we do not know the value of $|g_{ee}|$, it is convenient to write the total momentum transferred to the core in terms of the energy taken away by Majorons, $E_\Phi = xE_{\rm total}$:

$$\begin{aligned} \int d\vec{P} &= \frac{\sqrt{2} G_F n_e E_{\rm total} x}{2|V_e|} \langle \vec{\lambda}_e \rangle \\ &= -\frac{\sqrt{2} G_F E_{\rm total} x e}{4|V_e|} \left(\frac{3n_e}{\pi^4}\right)^{1/3} |\vec{B}| \hat{z}. \end{aligned} \quad (12)$$

The value of $|V_e|$ changes with time because of the loss of the electron lepton number through neutrino and Majoron emission. Calculating the exact time-dependence of $|V_e|$ is beyond the scope of this paper. Here we take a typical value of 0.5 eV for $|V_e|$ to estimate the order of magnitude of the effect.

In order that a star of mass M_s gains a velocity of v, the magnetic field has to be as large as

$$\begin{aligned} |\vec{B}| = &\left(\frac{M_s}{1.4\ M_\odot}\right) \left(\frac{v}{500\ {\rm km/s}}\right) \left(\frac{3 \times 10^{53}\ {\rm erg}}{E_{\rm total}}\right) \\ &\times \left(\frac{V_e}{0.5\ {\rm eV}}\right) \left(\frac{0.05\ {\rm fm}^{-3}}{n_e}\right)^{1/3} \left(\frac{0.5}{x}\right) 3 \times 10^{16}\ {\rm G}. \end{aligned} \quad (13)$$

Little is known about the magnetic fields in the core of a hot neutron star at birth. Observations show that magnetic fields at the *surface* of an average radio pulsar millions of years after birth are of the order of 10^{12} G. However, some of the observed neutron stars appear to have surface magnetic fields as high as 10^{15} G [16]. It is reasonable to assume that the field in the core of a neutron star is stronger than it is on the surface. It is also likely that the magnetic field inside a typical neutron star grows to $\sim 10^{16}$ G or higher during the first seconds after the onset of a supernova explosion due to a dynamo action [17]. This field subsequently evolves and decays during the later stages of neutron star cooling. An assumption that all neutron stars have strong interior magnetic fields at birth is not in contradiction with any of the present data.

We conclude that, if the Majorons carry away a substantial fraction of the released energy, they can give the pulsar high enough velocity to explain the data.

III. EFFECTS OF $\nu_\mu\nu_\mu \to \Phi$ AND $\bar{\nu}_\mu \to \nu_\mu\Phi$

The distributions of $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\tau$ in a supernova core are thermal; however, the densities of these neutrinos are substantially lower than that of ν_e: $\mu_{\nu_\mu} = \mu_{\nu_\tau} = 0$ and $T \ll \mu_{\nu_e}$. For the evolution of a neutron star, ν_μ and ν_τ are approximately equivalent. So hereafter we collectively call them ν_μ to avoid repetition. In a supernova core, V_μ is negative and as a result, the two processes $\nu_\mu\nu_\mu \to \Phi$ and $\bar{\nu}_\mu \to \nu_\mu\Phi$ can occur. In analogy with the $\nu_e\nu_e \to \Phi$ case, one can show that in the presence of a strong magnetic field a net momentum will be imparted to the supernova core, given by

$$\begin{aligned} \int d\vec{P} &= \frac{\sqrt{2} G_F n_e E_{\rm total} x}{6|V_\mu|} \langle \vec{\lambda}_e \rangle \\ &= -\frac{\sqrt{2} G_F E_{\rm total} x e}{12|V_\mu|} \left(\frac{3n_e}{\pi^4}\right)^{1/3} |\vec{B}| \hat{z}. \end{aligned} \quad (14)$$

Again if $x \gtrsim 0.1$ and $|\vec{B}| \sim 10^{16}$ G, neutron stars can gain high enough velocities.

IV. DISCUSSIONS AND CONCLUSIONS

In this paper we have shown that despite the strong bounds on the Majoron couplings to neutrinos, an asymmetric emission of Majorons can explain the high velocities of pulsars, provided that a substantial fraction of the binding energy of the star is emitted in the form of Majorons ($E_\Phi/E_{\rm total} \gtrsim 0.1$). The asymmetric emission can be caused by a magnetic field of order of 10^{16} G in the supernova core. Such high magnetic fields are quite possible in a supernova core [17].

The bulk of Majorons are produced deep inside the core, where the structure of the magnetic field is unknown. Surface magnetic fields are measured at much later times, when the neutron star is very cold. One does not expect a significant correlation between the field inside the core during the first seconds of a supernova explosion and the field on the surface of a cold neutron star that emerges from this explosion. As a result, we do not expect a correlation between the pulsar velocity and its observed magnetic field (the so called B–v correlation).

As was suggested by Spruit and Phinney [18], the mechanism responsible for the large pulsar velocities can also cause large angular momenta of pulsars. The emission of Majorons can give rise to a high angular momentum, provided that the magnetic field is not rotationally symmetric. The dynamo mechanism [17] can generate an off-centered dipole component if the convection at intermediate depths is faster than in the center. The latter is, indeed, likely because the negative entropy and lepton number gradients necessary for convection can develop in the outer regions, cooled by the neutrino emission.

Acknowledgments We are grateful to J. Valle for useful discussions. G. G. and Y. F. thank Aspen Center for Physics for hospitality during their stay, when a part of this work was done. The work of Y. F. was supported in part by DOE grant DE-AC03-76SF0051 and the Iranian chapter of TWAS at ISMO. The work of G. G. and A. K. was supported by DOE grant DE-FG03-91ER40662 and NASA grants ATP02-0000-0151 and ATP03-0000-0057.

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